Structure and Evolution of The Intergalactic Medium: Conference Summary

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Abstract. Wasn't this a fun meeting? Yes, except for the rain. This summary highlights four scientific themes of the 13$^{\rm th}$ IAP conference, plus a "wishlist" of future projects for observers and theorists.

1 Introduction: A Privileged Era?

In agreeing to summarize the results of this meeting, I had a few moments of doubt. First, we were all dismayed not to benefit from John Bahcall's 30 years of wisdom in the field. Second, a responsible effort would require many hours of close attention to 4.5 days of fascinating talks, diverting time from beautiful walks and museums. Most of all, I had a lingering concern that, on the last day of the conference, Jerry Ostriker would arrive from Princeton, just in time to set us straight! As it turned out, this was an enjoyable task, with stimulating talks on new data and new ideas.

I believe our field of QSO absorption-line studies is in a privileged era. Like the Roman god Janus, we look backward toward the past and forward to the future, both in our scientific tools and our theoretical paradigms (Table 1).

Table 1. Examples of "Janus-Like Era"

The Past	$\longleftarrow$ | $\longrightarrow$	**The Future**
4-meter telescopes	....	8-10 meter telescopes
Galactic halos	....	CDM/hydro paradigm
Interstellar models	....	Cosmological models
Lyα clouds + IGM	....	The "cosmic web"

Since the discovery of the high-redshift Lyα forest over 25 years ago, these absorption features in the spectra of QSOs have been used as evolutionary probes of the intergalactic medium (IGM), galactic halos, and now large-scale structure and chemical evolution. It is fascinating how rapidly our interpretation of these absorbers has changed, since they were interpreted as relatively small (10 kpc), pressure-confined clouds of zero-metallicity gas left over from the era of recombination. To be sure, the lack of strong clustering in velocity provided ample grounds for distinctions from QSO metal-line systems and galactic halos. However, these distinctions are clearly weakening.

In the next few years, I expect that many of the divisions between research in "interstellar" and "intergalactic" matter and between "QSO absorption clouds" and "cosmological structure" will fade away. We may even begin to understand more about how galaxies and their halos were assembled. Replacing the individual area studies will be a number of hybrid problems:

- CDM/Hydrodynamics + Feedback from star formation
- Interface between galaxies, the ISM, and the IGM
- Chemical evolution and heavy-element transport
- Reionization and the assembly of galaxies

Substantial portions of our July 1997 meeting were spent discussing these issues. Because I cannot do justice to all the individual talks (65 by my count), I will instead describe several outstanding problems in four scientific areas: (1) *The History of Baryons*; (2) *The History of Metals*; (3) *Reionization of the IGM*; and (4) *The Assembly of Galaxies.* I will conclude by providing "wish lists" of scientific projects for observers, instrumentalists, and theorists.

2 Major Themes of the Conference

2.1 The History of Baryons

One of the compelling reasons to study intergalactic Lyα clouds is that they may contain an appreciable fraction of the high-z baryons. To the extent that the Lyα absorbers are associated with large-scale structure and galaxy formation, the evolution of the IGM should parallel the evolution of galaxies and the history of baryons. Therefore, a major task is to understand the physical significance of various features in the column-density distribution of Lyα absorbers. As shown in Figure 1, Lyα absorbers range over nearly 10 orders of magnitude in H I column density, roughly from 10^{12} cm^{-2} to 10^{22} cm^{-2}. At the lower end, the *Keck* Telescope has detected weak Lyα absorption down to log $N_{HI} \approx 12.3$. At the upper end, damped Lyα absorbers have been seen up to log $N_{HI} \approx 21.6$. What are the physical reasons for this range and for features in the approximate power-law distribution? More specifically, we should be concerned about the following questions and issues:

- Is there a turnover in the distribution at log $N_{HI} \leq 12.7$? These weak absorbers, which may arise in very low-density regions of the IGM, may produce substantial He II absorption toward high-z QSOs.
- What is the physical significance of the steepening in the distribution above $N_{HI} = 10^{14.5}$ cm^{-2}? This turnover has been noticed for years, but it was difficult to verify owing to curve-of-growth uncertainties. Clouds at 10^{14-15} cm^{-2} may contain most of the baryons in the Lyα forest (for

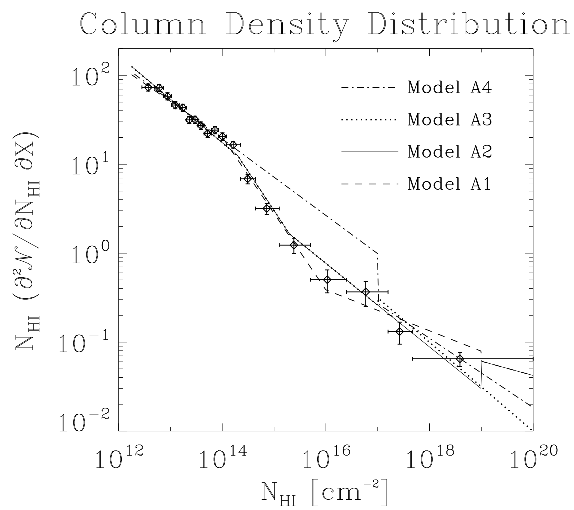

Figure 1: Column density distribution of Lyα clouds at mean redshift $\langle z \rangle = 3$, based on *Keck* and other spectra (see Fardal, Giroux, & Shull 1997). The variable $dX = (1+z)dz$ is the "absorption length" (Petitjean et al. 1993). Model A2 is a preferred fit with a turnover above $10^{14.5}$ cm^{-2}.

a $N_{\rm HI}^{-1.5}$ distribution). Clouds at $10^{14.5-15.5}$ cm^{-2} are used for double-QSO cloud size estimates and for metal-line detections of C IV and Si IV. We need to understand their structure and shape.

- Can we detect the transition from atomic (H I) to molecular (H_2) gas in the damped Lyα absorbers? The expected turnover should be seen above log $N_{\rm HI} \approx 21.5$ and related to high-redshift CO and the first stars.

- For chemical evolution models, it is important to reconcile the baryon evolution rate, $\dot{\Omega}_b$, with the star formation rate, $\dot{\Omega}_*$ and the metal formation rate, $\dot{Z}$. What is the role of the IGM in this network? The Lyα forest probably contains substantially more baryons than the damped Lyα absorbers ($\Omega_{\rm LF} \approx 10\,\Omega_{\rm DLA}$). The metallicity of the Lyα forest is $10^{-2.5\pm0.5}$ solar, while that of the damped Lyα absorbers is $10^{-1.5\pm0.5}$ solar. The larger baryon reservoir in the forest may therefore be a significant part of the metal inventory.

2.2 The History of Metals

Five years ago, most astronomers believed the Lyα forest clouds to be pristine. The observations that a high percentage of Lyα clouds with $N_{\rm HI} \geq 10^{14.5}$ cm^{-2} contain heavy elements (C IV, Si IV) were astonishing. Recent estimates of the metal abundance are $10^{-3.0}$ to $10^{-2.5}$ times solar metallicity and suggest a

(Si/C) enhancement by about a factor 2 over solar ratios. The Si IV lines are especially interesting, since Si is thought to be formed by α-capture processes in massive stars and expelled by Type II supernovae. We need to clarify some implications of these data:

- Where and when were the heavy elements formed? Although the *Hubble* Deep Field and related observations suggest that the bulk of metal production and star formation occurred at $z = 1 - 2$, the metals in the Lyα forest obviously formed earlier. How much earlier? Was it in disks, dwarf galaxies, or low-mass objects such as proto-globular clusters? Were these metals blown out, stripped by mergers, or transported by other means? Understanding these processes may clarify the "astration" of deuterium by the first generations of stars.

- Wherever the heavy elements were produced, they cannot have been transported far from their source. Over 1 Gyr, metal-laden gas moving at 100 km s^{-1} would travel 100 kpc, approximately the size of typical galactic halos and some Lyα clouds. Local effects from massive star formation could cause the ionization states of Si and C to differ significantly from pure QSO photoionization. A key experiment would be to infer the size of the metal-bearing Lyα clouds from double-quasar coincidences. However, these moderate-column (log $N_{HI} > 14.5$) clouds are sufficiently rare that good statistics will be difficult to obtain.

- Converting the observed N(Si IV)/N(C IV) to accurate Si/C abundances requires a clear understanding of the ionization mechanism (photoionization versus collisional ionization). If photoionization, we need a much better idea of the spectral shape, $J_\nu(z)$, produced by quasars and starburst galaxies at redshifts $z = 2 - 5$. The photon range from 2–5 Rydbergs is particularly important, since it covers the ionization edges of relevant Si and C ions. In the Lyα forest, it is important to understand the Si IV/C IV ratios, component by component, as is often done in the analysis of interstellar absorption profiles.

- The abundances of the iron-group and other elements (Fe, Ni, Zn, Si, Cr) in the damped Lyα systems need to be confirmed. Their ratios provide strong suggestions of massive-star nucleosynthesis and hints of dust depletion. Zinc may provide particularly important clues.

- I was impressed by attempts to invert the Mg II, Fe II, and C IV line profiles to produce kinematics of the metal-line absorbers. However, I suspect that in most cases the inversion is not unique; departures from simple orbits are likely, as shocks and gas dynamics are important.

2.3 Reionization of the IGM

Most of us carry a mental picture that the IGM was reionized at high redshift ($z \geq 5$) by the first quasars and first massive stars. There are hints that it

could occur even earlier. However, the redshift history of reionization is poorly known, except for theoretical prejudices based on CDM models for structure formation. Up to $z \approx 4$, the quasar luminosity function is fairly well known, but the same cannot be said of quasars at $z > 4$ or of starburst galaxies at any redshift. The following issues remain controversial:

- Are there missing QSOs at $z > 4$ owing to dust obscuration? Theoretical suggestions (Fall & Pei 1989) of a substantial population of "missing quasars" have not yet been confirmed. There are hints of dust depletion from Zn/Cr ratios in damped Lyα systems, and conflicting results from red- and radio-selected high-z quasars. One recent QSO luminosity function (Pei 1995) produces too few Lyman continuum photons to reionize hydrogen by $z = 4$. Thus, additional ionizing sources are needed: either QSOs or starburst galaxies.

- When were the *first* O stars? If massive star formation is a natural result of the first star formation, then these objects will dominate the feedback to the gaseous environment, including dissociation of H_2, production of key heavy elements (O, Si, S), and generation of large volumes of hot gas through supernovae and stellar winds. The details of this feedback depend on the galactic environment (dwarfs, spirals, halos).

- How much of the energy input to the IGM is mechanical? Massive stars produce both hot gas and ionizing radiation. If the "mechanical" energy input is released through blast waves, the affected volume scales with energy as as $E^{3/5}$, whereas metal production scales as E. Thus, low-luminosity sources (dwarf galaxies) may dominate metal dissemination.

- Have we detected the era of helium reionization? Dieter Reimers showed us intriguing evidence for patchy He II absorption toward a quasar at $z = 2.9$. Can this be reconciled with Gunn-Peterson observations at $z \approx 4.7$ that suggest reionization in hydrogen? Theoretical models of the QSO luminosity function and IGM opacity suggest that the IGM should be reionized in He II at $z \geq 3.3$. Perhaps this is evidence for hot-star ionizing sources, with little 4 Ryd (He II) continuum.

Observations are badly needed to push our understanding of the reionization epoch back to $z \geq 5$. First, we need to find QSOs at $z > 4.9$, perhaps from the Sloan Sky Survey. Possible probes of the high-z era include searches in the radio, microwave, far-infrared, and near-infrared bands. As planning begins for the NGST (Next Generation Space Telescope), the infrared band ($1 - 5$ μm) offers promise for deep searches for high-z, dust-obscured QSO as well as high-z supernovae. Detecting 21-cm emission at $z > 5$ might be possible with a sufficiently large array of radio dishes. The Lyα absorption from the neutral IGM prior to reionization might show up in high-z spectra of quasars at $z \approx 5$. To probe even higher redshifts, one might consider searches for redshifted metal fine-structure lines such as [C II] 158μm and [O I] 63μm, which would appear at (1.6 mm)$[(1+z)/10]$ and (630 μm)$[(1+z)/10]$.

2.4 The Assembly of Galaxies

The standard (CDM) model of galaxy formation predicts a "bottom-up" hierarchy of structure formation. If clumps of $10^{5-7}\ M_\odot$ form massive stars at $z > 3$, they could have significant effects on Lyman continuum radiation, hot gas, and heavy-element transport. If the sub-clumps form in the halos of proto-galaxies, or fall in gravitationally, cloud-cloud collisions are likely to occur. What are the implications of the resulting shock waves for line profiles of Mg II and C IV absorbers? Shocks will generate hot gas at $T \approx (10^5\ \mathrm{K})[V/100\ \mathrm{km\ s^{-1}}]^2$, sufficient to produce C IV by collisional ionization. Are the observed line profiles evidence for such effects?

Finally, we heard several speakers speculate on the formation of large gas disks in the context of damped Lyα absorbers. Are these DLAs actually thick disks of 30 kpc size or 5–8 kpc clumps as predicted by some numerical modelers? If the DLAs are as small as 5–8 kpc, it may be difficult to understand their frequency, $d\mathcal{N}/dz$, and there may be an angular momentum problem. Following the implications of the CDM scenario, how are the small pieces of proto-galaxies assembled? What are the roles of radiative cooling and sub-clump mergers?

3 A Wish-List for the Future

I conclude this review with lists of ideas and scientific tools for workers in our field. I have given separate discussions for observers and theorists.

3.1 Observers and Instrumentalists

I continue to be amazed by the beauty of the HIRES spectra taken by the *Keck Telescope*. These new optical data have changed the field of QSO absorption lines in so many areas. My first wish is that the new 8–10^m telescopes and spectrographs become sufficiently productive to compete with *Keck*. Even though many astronomers are actively using *Keck* for QSO studies, we can foresee the time when several new telescopes come on line: the *Hobby-Eberly Telescope*, the *VLT*, and *Gemini*.

A general lesson learned from the *Keck* experience is that high-resolution spectroscopy is one of the most powerful tools in astrophysics. That power should be extended to other wavelength bands. Large instruments are needed:

- **Ultraviolet:** To study D/H evolution, the He II Gunn-Peterson effect, chemical evolution of metals, and damped Lyα systems, we need a UV spectrograph with effective area $\sim 10^4\ \mathrm{cm}^2$. For comparison, the current spectrographs aboard *Hubble* have $A_{\mathrm{eff}} \approx 100 - 200\ \mathrm{cm}^2$ for moderate-resolution (30-50 km s^{-1}). In 2002, HST will be upgraded with the *Cosmic Origins Spectrograph*, which will provide 1000-1500 cm^2 effective

area. The next generation of UV instruments should consider taking another factor-of-ten step in spectroscopic throughput.

- **Infrared & Sub-millimeter:** Both the NGST and FIRST telescopes are designed to provide 4-meter apertures that access the near-IR and sub-mm respectively. These instruments should provide powerful imaging of the era beyond redshift $z = 5$. The spectroscopic capabilities may provide further surprises for detecting protogalaxies along with their first stars and supernovae.

- **Millimeter:** As noted earlier, relating the damped Lyα absorbers (protogalactic gaseous disks) to the first spiral galaxies will require us to follow the transition from atomic to molecular gas (from H I to CO). The mm-array offers the chance to make these comparisons.

- **X-Ray:** The equivalent X-ray instrument for high-resolution spectroscopy with sufficient throughput to match the optical could be the HTXS ("High Throughput X-Ray Spectroscopy") mission. Designed with 1–10 m^2 of effective area, this set of X-ray telescopes would have the capability of studying the "X-ray Gunn-Peterson effect" in heavy-element K-edge absorption through the metal-contaminated parts of the IGM. These observations could detect the hot gas invisible in H I and He II absorption. These absorption signatures are expected to be extremely weak ($\tau \approx 10^{-3}$).

3.2 Simulations and Modelers

Many of the talks at this meeting worked within the new cosmological paradigm for the Lyα clouds. Over the past five years, numerical models have increased their accuracy and predictive power immensely, to the point where they are now able to provide constraints on Ω_b, J_ν, and galaxy formation. There is still some ways to go, however, and I offer the following wishes:

- Computers are increasing in their speed and capacity. Many of us, including the modelers, anticipate seeing their simulations run to $z \to 0$ and computed in a box of size $100h^{-1}$ Mpc.

- The models need a better justification for the redshift at which quasars and star formation turn on. As noted earlier (§2.3) we have little information on these epochs of reionization.

- The models need to incorporate better small-scale physics. I have the impression that the gravitational collapse of large-scale gaseous structures is treated fairly well. However, once stars and quasars turn on, the microphysics [supernovae, stellar winds, superbubbles, heavy element transport, hot gas, radiative transfer] needs to be handled in a realistic fashion. These "local effects" are the next hurdle in complexity.

- To agree with the H I column density distribution, the numerical models require a lower ionizing radiation field than that inferred from the proximity effect. Models for the Lyα absorber distribution constrain the ratio (Ω_b^2/J_{-21}), where J_{-21} is the specific intensity at the Lyman limit, in units of 10^{-21} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}. These parameters need to be reconciled with independent inferences of the baryon density from deuterium measurements, $\Omega_b h^2 \approx 0.020 \pm 0.015$ (Tytler 1997), and of the radiation field $J_{-21} \approx 0.5 - 1.0$ (Giallongo et al. 1996; Cooke et al. 1997). Some of the models described at this meeting suggest a sizeable discrepancy. For example, Zhang et al. (1997) require a photoionization rate $\Gamma_{\rm HI} = (3 - 10) \times 10^{-13}$ s^{-1}, which corresponds to $J_{-21} \approx 0.1 - 0.4$ for background spectral slope $\alpha_b \approx 1.8$.

- Fluctuations in the ionizing background are quite important and should be included in the models. The patchy He II absorption reported by Reimers may be one manifestation of this. More generally, the baryons are not exposed to a constant, optically-thin radiation field.

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